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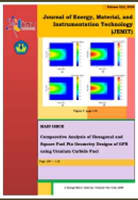

Comparative Analysis of Hexagonal and Square Fuel Pin Geometry Designs of GFR using Uranium Carbide Fuel

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Abstract

Comparative Analysis of Hexagonal and Square GFR Fuel Pin Geometry Designs with Uranium Carbide Fuel has been carried out. Nuclear reactors from Generation I to IV have developed significantly, with Gas-cooled Fast Reactors (GFR) being a potential candidate for operation by 2030. This study focuses on a GFR reactor utilizing uranium carbide (UC) fuel with a low input power of 300 MWth. The reactor core adopts a cylindrical pancake geometry with 100 cm height and 240 cm diameter dimensions. The objective is to compare the optimal design between hexagonal and square pin cell geometries for GFR-type fast reactors. The study employs the SRAC 2006 software with the JENDL 4.0 database. The research involves homogenous core configuration calculations, heterogeneous core configuration calculations, and variations in fuel fraction to determine optimal data for hexagonal and square pin cell configurations. Results indicate that heterogeneous fuel configurations require fuel fractions of 51% for hexagonal pins and 59% for square pins, with comparable maximum power performance at End of Life (EOL) and Beginning of Life (BOL). It suggests that hexagonal pins are more efficient, requiring less fuel material to maintain reactor criticality over a 20-period burn-up.

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Abstrak

Analisis perbandingan desain geometri pin bahan bakar heksagonal dan persegi pada Reaktor Cepat Tipe Gas-cooled Fast Reactor (GFR) dengan bahan bakar Uranium Karbida telah dilakukan. Reaktor nuklir dari Generasi I hingga IV telah mengalami perkembangan signifikan, dengan Gas-cooled Fast Reactor (GFR) menjadi kandidat potensial untuk dioperasikan pada tahun 2030. Penelitian ini berfokus pada reaktor GFR yang menggunakan bahan bakar uranium karbida (UC) dengan daya masukan rendah sebesar 300 MWth. Inti reaktor menggunakan geometri silinder pancake dengan tinggi 100 cm dan diameter 240 cm. Tujuan penelitian adalah membandingkan desain optimal antara geometri sel pin heksagonal dan persegi untuk reaktor cepat tipe GFR. Penelitian ini menggunakan perangkat lunak SRAC 2006 dengan basis data JENDL 4.0. Penelitian melibatkan perhitungan konfigurasi inti homogen, konfigurasi inti heterogen, dan variasi fraksi bahan bakar untuk menentukan data optimal pada konfigurasi sel pin heksagonal dan persegi. Hasil penelitian menunjukkan bahwa konfigurasi bahan bakar heterogen memerlukan fraksi bahan bakar sebesar 51% untuk pin heksagonal dan 59% untuk pin persegi, dengan kinerja daya maksimum yang sebanding pada End of Life (EOL) dan Beginning of Life (BOL). Hal ini menunjukkan bahwa pin heksagonal lebih efisien, memerlukan jumlah material bahan bakar yang lebih sedikit untuk mempertahankan kritikalitas reaktor selama periode burn-up 20 tahun.

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1. Introduction

Energy can be divided into two types: renewable energy and non-renewable energy. Renewable energy is energy that is sourced in nature. Renewable energy can also be renewed and not wasted continuously (Rumbayan M, 2020)). Nuclear energy is one of the most renewables. Nuclear energy can cover various shortcomings of other energy sources, such as efficiency problems and energy sources that are quickly depleted (Alimah S and Dewita E, 2008). Nuclear energy has a positive impact that can reduce greenhouse gas emissions. It affects the competitiveness of nuclear energy with non-renewable energy that exists today (Hasan Y, 2015). Nuclear energy is used as an energy source for nuclear power plants. A nuclear power plant is a facility that converts atomic energy into usable power (Department for Economic and Social Information and Policy Analysis New York, 1997).

Nuclear power plants utilize nuclear reactors to process nuclear energy sources. One of the reactors used is a gas-cooled fast reactor (GFR) type fast reactor (Mulyaman M, 2008). GFR reactors fall into the category of small modular reactors (SMRs). SMRs are small reactors with less than 300-megawatt electrical (MWe) (Locatelli et al., 2014). The development of the current GFR reactor is the development of high-temperature fuel material elements and safety architectures that follow the objectives of the Generation IV International Forum program (Pioro I.L, 2016). The use of high temperatures in fuel also has the opportunity to produce hydrogen gas as an alternative energy source (Prasetya *et al.*, 2024). By 2025, GFR-type fast reactors are expected to be ready for commercial use (Anggoro Y.D et al., 2013). A fast reactor is a reactor that undergoes a fission reaction with the dominance of fast neutrons. It significantly reduces the material to the moderator material (Ariani M et al., 2010).

According to Syarifah et al. (2017), in comparative studies of variations in reactor core design on the 300MWth GFR powered by uranium-plutonium nitride (UN-PuN) without refueling, the most optimal core design obtained is in the design of balance cylinder core geometry. In the geometry of the core, the value of k-eff has a flatter and more stable value than the geometry of the core pancake and tall cylinders. The study used the 2006 SRAC calculation code and the JENDL 4.0 data library. In addition, some reactor design parameters are the design of heterogeneous core variation reactor radial and axial directions.

According to research by Sabrina A.N et al. (2020) on the design of GFR using uranium-plutonium carbide (UC-PuC) as a fuel with the addition of protactinium (Pa-231), which aims to analyze the performance of UC-PuC as a fuel of GFR reactors coupled with additional material in the form of Pa-231. The optimal result obtained is in the variation of the addition of protactinium 4% with a fuel fraction of 63%. The study used the 2006 SRAC calculation code with the data library JENDL 4.0. In addition, the reactor design parameters used are a pancake cylinder core with a height of 100 cm and a diameter of 240 cm and the geometry of hexagonal fuel pin cells.

Another GFR study is related to analyzing the volume fraction of uranium carbide fuel in gas-cooled fast reactors using the SRAC code conducted by Syarifah et al. (2021). The study used fuel cell pin calculation (PIJ calculation) and reactor core calculation (CITATION calculation). Both calculations were performed using SRAC code and retrieved library data from JENDL 4.0. The geometry of the reactor core is used in the form of a pancake cylinder with 240 cm diameter and 100 cm height core. The results obtained in the study were optimal design achieved at a fuel volume fraction of 49% with the heterogeneous core configuration of three types of fuel percentage. The three percentages of fuel are fuel type 1 by 9%, fuel type 2 by 12%, and fuel type 3 by 15%.

Another GFR study studies the addition of neptunium, americium, and protactinium for GFR 300MWth with uranium carbide fuel. The study was conducted to determine the characteristics of some additional fuel material in the 300MWth GFR reactor. Some of these materials include neptunium, americium, and protactinium. The result at the beginning of the burn-up phase of additional material gives rise to a reduction in the value of k-eff. While at the end of the burn-up period, the material that can reduce the value of k-eff is protactinium material. It is known that protactinium material is often referred to as burnable poison (Syarifah R.D et al., 2019).

Another GFR research related to neutronic analysis of comparison uranium-plutonium nitride fuel and thorium nitride fuel for 300MWth gas-cooled fast reactor long life without refueling. The study used the SRAC calculation code. The PIJ method is used to calculate the hexagonal pin cells, and the CITATION method is used to calculate the reactor core. Uranium-plutonium nitride fuel uses fissile material in plutonium and fertile material in natural uranium. Thorium nitride fuel uses fissile material in uranium-235 and fertile material in natural thorium. The result is that uranium-plutonium nitride fuel has a maximum power density value smaller than thorium nitride fuel. It suggests that uranium-plutonium nitride fuel is more efficient in GFR-type reactors powered by 300MWth (Syarifah R.D et al., 2020).

Based on some of these studies, this study was conducted as a follow-up study of these studies. The study aimed to compare the geometry of hexagonal and square fuel pin cells in uranium carbide (UC) fuel-fueled GFR reactors with a power of 300 MWth. In addition, the calculation code used is the same as that used in previous studies of SRAC 2006 with the JENDL 4.0 data library. The reactor design used in this study is a pancake cylinder with a height of 100 cm, a diameter of 240 cm, and a heterogeneous core variation design of axial direction.

2. Research Methods

This study compared the variation of geometric pin cells using two types of pin cell designs, hexagonal and square, with a power of 300 MWth. The fuel used is uranium carbide with a coolant in helium gas. This study used the SRAC code (Standard Reactor Analysis Code) version 2006 and data sources from JENDL 4.0 to produce data that needed processing and analysis. Standard thermal reactor analysis code or SRAC is designed to calculate neutronic calculations in nuclear reactors. The system can calculate various types of thermal nuclear reactors (Okumura K et al., 2002). The comparative research flow of fuel pin geometry is shown in **Figure 1**. The initial step in this research is to prepare reactor design and fuel cell specifications. The specification data is written into the SRAC program, which is then executed using the PIJ module and run CITATION. Calculations are carried out in stages starting from the homogeneous core configuration, the heterogeneous core configuration stage, and variations in fuel fraction until reaching the optimal design. Homogeneous reactor cores have the same fuel enrichment for each fuel pin, while heterogeneous reactor cores use several variations in fuel enrichment distributed in certain fuel pin configurations (Syarifah R.D et al., 2023).

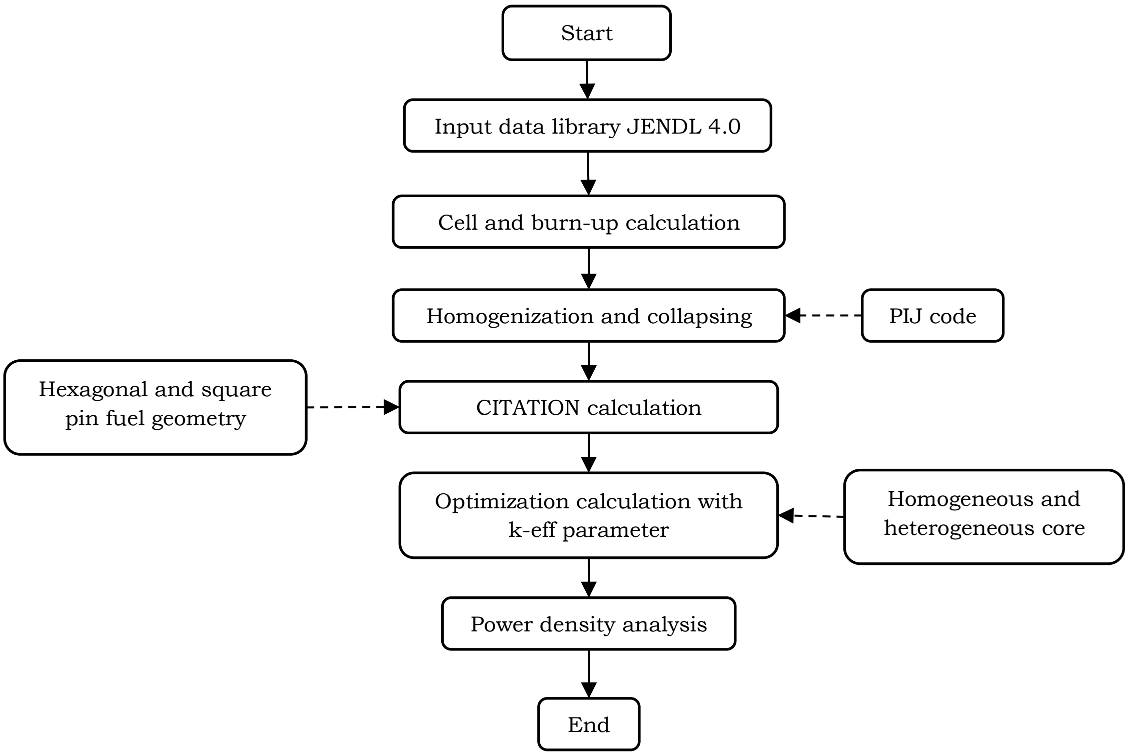


Figure 1. Research flow

This research is divided into several stages to obtain the desired final data. Based on **Figure 1**, the first stage involves homogeneous core configuration calculations with a coolant, cladding, and fuel ratio of 30%: 10%: 60%. Optimization in this stage is achieved by varying the enrichment of U-235. Enrichment data is inputted and computed using the PIJ module to obtain the k-inf value. The PIJ results are then used as reference data in the CITATION calculation module to assess the criticality of all reactor components and determine the k-eff value. Heterogeneous fuel variations are calculated with the same coolant, cladding, and fuel ratio as the homogeneous case but divide the fuel into 3 regions: F1, F2, and F3, as shown in **Figure 3**. The most optimal heterogeneous configuration results are then used as a reference to vary the volume fraction of fuel in the core by adjusting coolant and fuel fractions. The computed optimal fuel volume fraction for hexagonal and square pin geometries is further analyzed to obtain average power density and power distribution.

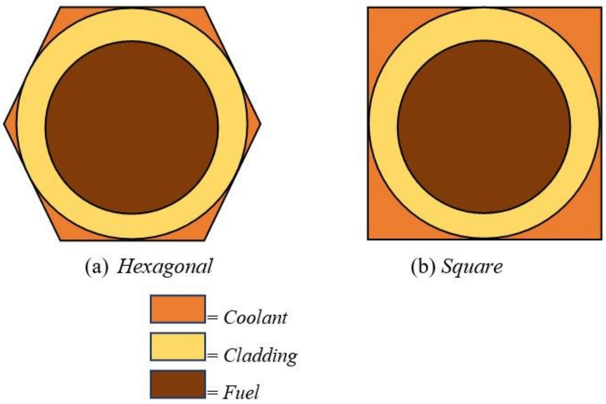


Figure 2. Hexagonal and square pin cell design

The study used an input power of 300 MWth with a burn-up period of 20 years. The core geometry used is a pancake cylinder with a diameter of 240 cm and a height of 100 cm. The geometry of the fuel pin cells used is hexagonal, and square fuel pin cells are shown in **Figure 2**. The fuel used is uranium carbide with a fraction of fuel volume, 45% to 60%. The percentage of uranium-235 material in the fuel uses a percentage variation in the field of 5% to 15%. The cladding material used is silicon carbide (SiC) with a volume fraction of 10%. The GFR reactor in this study used cooling in helium gas with a volume fraction of 30% to 45%. The design of the core of the research reactor is in the form of a pancake cylinder. The pancake cylinder is the geometry of the reactor core with a diameter design greater than its height. Reflectors surround the reactor core's design with wide reflectors on each side of the right, left, top, and bottom sides. In addition, the core section is divided to arrange the fuel pin cell. The division of the core is F1, F2, and F3. One fuel pin cell is set in one mesh. The size of this mesh is 5 cm. The diameter of the reflector used on each side is 50 cm. In addition, the F1 part has a width of 65 cm, the F2 part has a width of 35 cm, and the F3 part has a width of 20 cm. These three parts have different mesh numbers. F1 has 13 meshes, F2 parts as seven meshes, and F3 parts as four meshes. In addition, the core reactor heterogeneous variations in this study used axial directional cores, as shown in **Figure 3**.

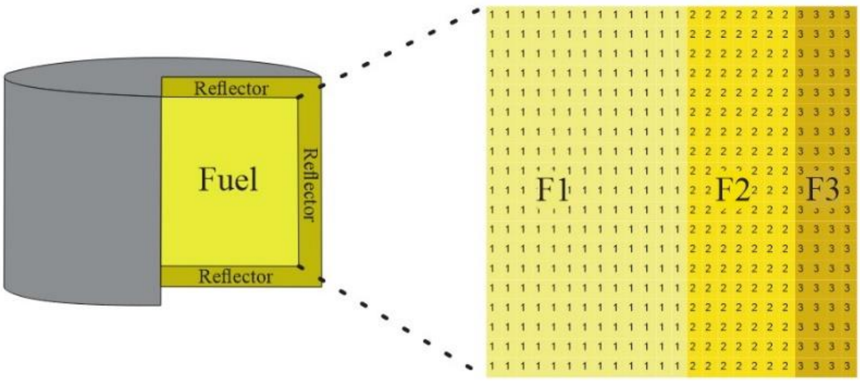


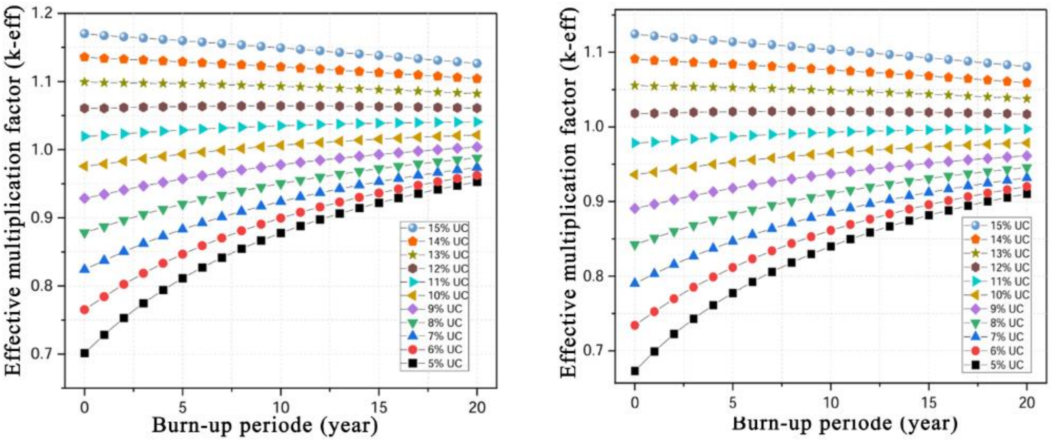
Figure 3. Heterogeneous core variations of axial directions

Optimization of the k-eff value at each calculation stage is based on the criticality characteristics of the reactor. The k-eff value must approach the critical state (k~1) at each burn-up period to be said to be the most optimal design variation (Mabruri et al., 2022). The critical state of a nuclear reactor is indicated by a value of k = 1, indicating very controlled neutron production, and a reactivity value = 0 (Duderstadt & Hamilton, 1976). It is very important in the safety analysis of a nuclear reactor to prevent accidents due to reactivity spikes. The excess reactivity value is calculated as $\Delta k/k$ and is said to be good if the value is close to 0%. $\Delta k/k$ is obtained from the value of k-eff minus the criticality constant (the value is 1) divided by the value of k-eff and multiplied by 100% (Syarifah R.D et al., 2024).

3. Results and Discussions

3.1 Calculation of homogeneous core

Homogeneous core configuration has been conducted with variations in U-235 enrichment percentage in uranium carbide (UC) fuel from 5% to 15% over a 20-year burn period. **Figure 4(a)** compares k-eff results for hexagonal pin geometry, while **Figure 4(b)** displays the same results for square pin geometry. The analysis found that a uranium enrichment percentage of 12% produces the lowest k-eff and approaches critical conditions at the end of the burn period for both geometries.



(a) (b)

Figure 4. Comparison of k-eff variations of homogeneous cores with cell pins; hexagonal (a) and square (b).

Figure 4(b) shows that pins with a square configuration can have smaller reactivity than hexagonal pins for the same uranium enrichment value in each burn-up period. The square configuration has a smaller fuel ratio in the core. It causes fewer fission reactions in hexagonal cores than in hexagonal configurations. The next stage is the heterogeneous core configuration stage and the variation in fuel fraction to determine the optimal k-eff value.

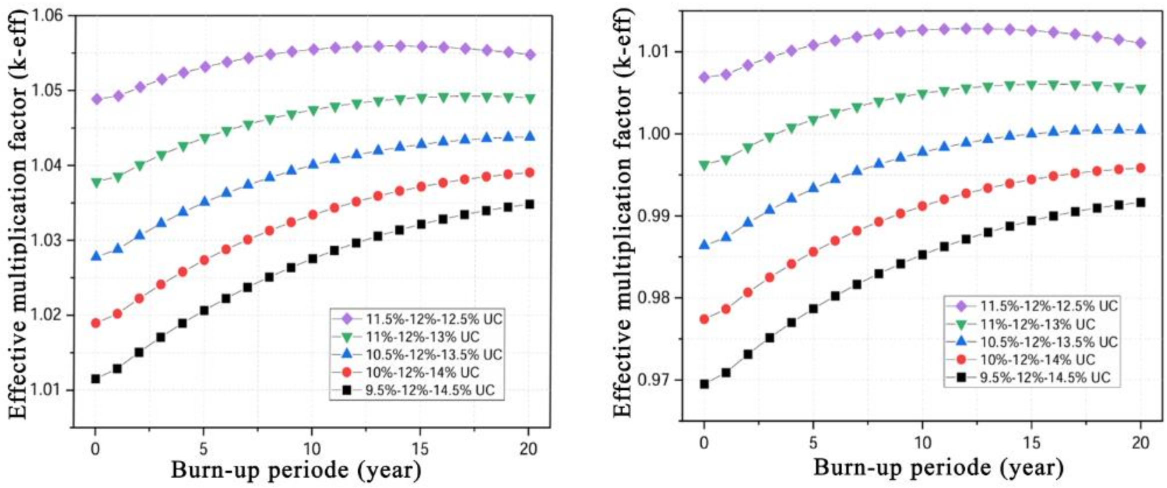
3.2 Calculation of heterogeneous core

Based on the results of the homogeneous core configuration carried out previously, a heterogeneous core configuration has been carried out using the percentage of U-235 enrichment. The core division is divided into 3 parts, as shown in **Figure 3**. The percentage distribution of F1, F2, and F3 varies according to **Table 1**.

Table 1. Percentage variation of U-235 enrichment in heterogeneous core configurations.

No.	Uranium – 235 percentages			Average
	F1	F2	F3	
1.	9.5%	12%	14.5%	12%
2.	10%	12%	14%	12%
3.	10.5%	12%	13.5%	12%
4.	11%	12%	13%	12%
5.	11.5%	12%	12.5%	12%

The percentage variations shown in **Table 1** are used for data collection in the heterogeneous core configuration stage. This study compares the total core fuel material to other core components, which have a ratio of 60%. Figure 5 compares heterogeneous core configuration results between hexagonal and square pin cell geometries. The results in **Figure 5(a)** show the k-eff value for hexagonal pin cells, while **Figure 5(b)** shows the k-eff value for square pin cells.



(a) (b)

Figure 5. Comparison of k-eff variations of heterogenous cores with cell pins; hexagonal (a) and square (b

The results in **Figure 5** show that the heterogeneous configuration can reduce the k-eff value for both hexagonal and square pin geometries. **Figure 5(a)** indicates that the hexagonal configuration has the potential to maintain criticality for 20 years across all variations. In contrast, the square configuration shown in **Figure 5(b**) can only achieve criticality for 20 years at enrichment percentage variations of 11.5%, 12%, and 12.5%.

3.3 Comparison of optimal fuel fractions

Based on the previous results in Figure 5, enrichment variations F1, F2, and F3 of 11.5%—12%—12.5% and a fuel fraction of 60% were used to approach the criticality condition for hexagonal and square pin configurations. These variations were then selected and adjusted to determine the optimal fuel fraction to further approach criticality. Fuel fraction variations in the reactor core varied within the 45-60% range, as shown in **Figure 6.**

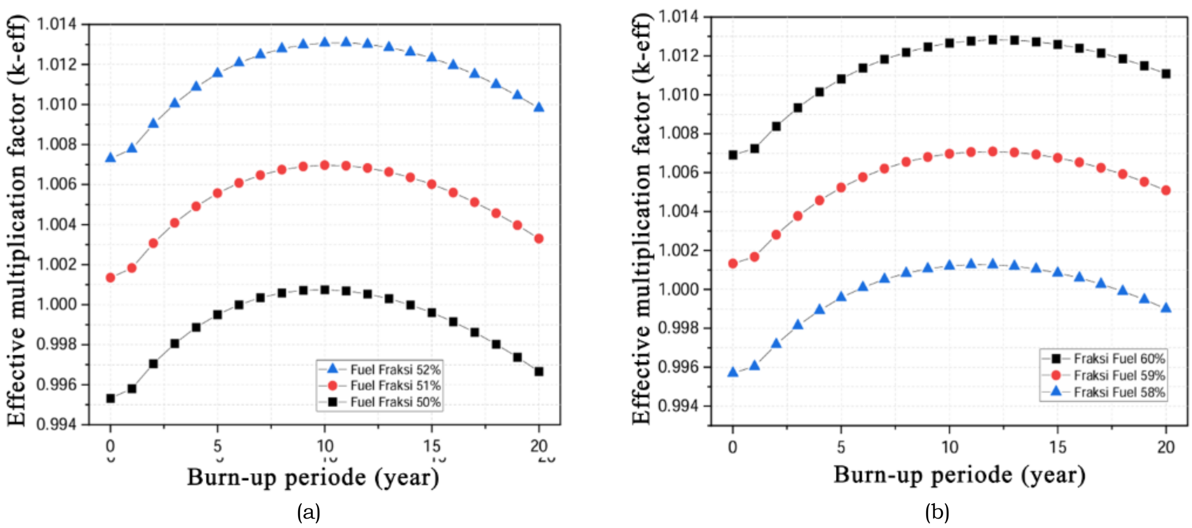


Figure 6. Optimal k-eff values in hexagonal and square pin cells

Figure 6 shows a significant decrease in the k-eff values due to changes in the fuel fraction of the reactor core. **Figure 6(a)** indicates that the optimal condition for hexagonal pins can be achieved with a fuel fraction variation of 51%. In contrast, **Figure 6(b)** shows that the optimal fuel fraction for square pins is 59%. The k-eff value for hexagonal pins peaks at the 10th burn-up year and the 12th year for square pins. In comparing these two optimal designs, the square pin design can sustain reactor criticality longer than the optimal hexagonal pin design. It is further supported by the end burn-up values in the 20th year, where square pins have a k-eff of 1.0050 compared to 1.0033 for hexagonal pins. Figure 6 shows a significant decrease in the k-eff value due to changes in the reactor core's fuel fraction. Figure 6(a) indicates that the optimal condition for hexagonal pins can be achieved with a fuel fraction variation of 51%.

In contrast, Figure 6(b) shows that the optimal fuel fraction for square pins is 59%. The k-eff value for hexagonal pins peaks in the 10th burn-up year, whereas it occurs in the 12th year for square pins. In the final comparison of these optimal designs, the square pin design can sustain reactor criticality longer than the optimal hexagonal pin design. It is further supported by the final burn-up values in the 20th year, where square pins have a k-eff value of 1.0050, whereas hexagonal pins are at 1.0033. However, the smaller fuel fraction indicates that less fuel material is required for the same burn-up period. Therefore, in this regard, hexagonal pins have an advantage because they require less fuel than square pins to sustain a 20-year burn-up period.

3.4 The power density of optimization hexagonal and square pin cells

Power density analysis in optimized hexagonal and square fuel pin designs is needed to see the level of power peaking generated from each condition. The observed condition consists of 2 parameters, i.e., BOL (Beginning of Life) and EOL (End of Life). Power density (Watt/cc) is important in measuring reactors' safety levels under certain value limits. The power density results are shown in **Figure 7**.

Figure 7a is a graph of power density distribution within half the core of the hexagonal pin cell geometry reactor with an optimal k-eff value at the beginning of life (BOL). BOL is a period of burn-up that occurs inside the reactor core in the first year. The power distribution shown in Figure 7(a) has the highest value in the middle of the reactor core. A reddish color characterizes it in the graph. Fission reactions in the reactor happen in the middle area of the reactor. The fewer fission reactions, the color shown, and the bluer. The blue stain on the edge of the reactor indicates no fission reaction in the area. That is because the blue area is a reflector that serves as a neutron reflector to return to the reactor core. The maximum power density distribution value obtained is 159 watts/cc. Figure 7(b) shows a graph of the power density distribution of hexagonal pin cells at the end of life (EOL). EOL is the final period of burn-up that occurs inside the reactor core. The highest power distribution value obtained is in **Figure 7b** in the red zone. The highest power density distribution occurs in the middle of the reactor core. Most fission reactions happen in the red area. The fission reaction in the middle of the reactor at EOL is more than the fission reaction in BOL. The maximum power density distribution value obtained is 170 watts/cc.

Figure 7c shows BOL's pin square cell power density distribution graph. The image shows the most extensive distribution of power density occurring in the middle of the reactor. The maximum power density distribution value obtained is 159 watts/cc. The maximum power density distribution value equals the maximum power density distribution value produced in hexagonal pin cells. **Figure 7d** shows a graph of the geometric power density distribution of pin square cells on the EOL. The reactor core in the middle is getting red. It indicates that the value of the power density distribution is increasing. In addition, the fission reaction in the middle of the reactor core is increasing. That causes the value of power density distribution in the middle of the reactor to get bigger. The maximum power density distribution value obtained is 168 watts/cc. The maximum power density distribution value is smaller than obtained in the hexagonal pin cell geometry phase EOL.

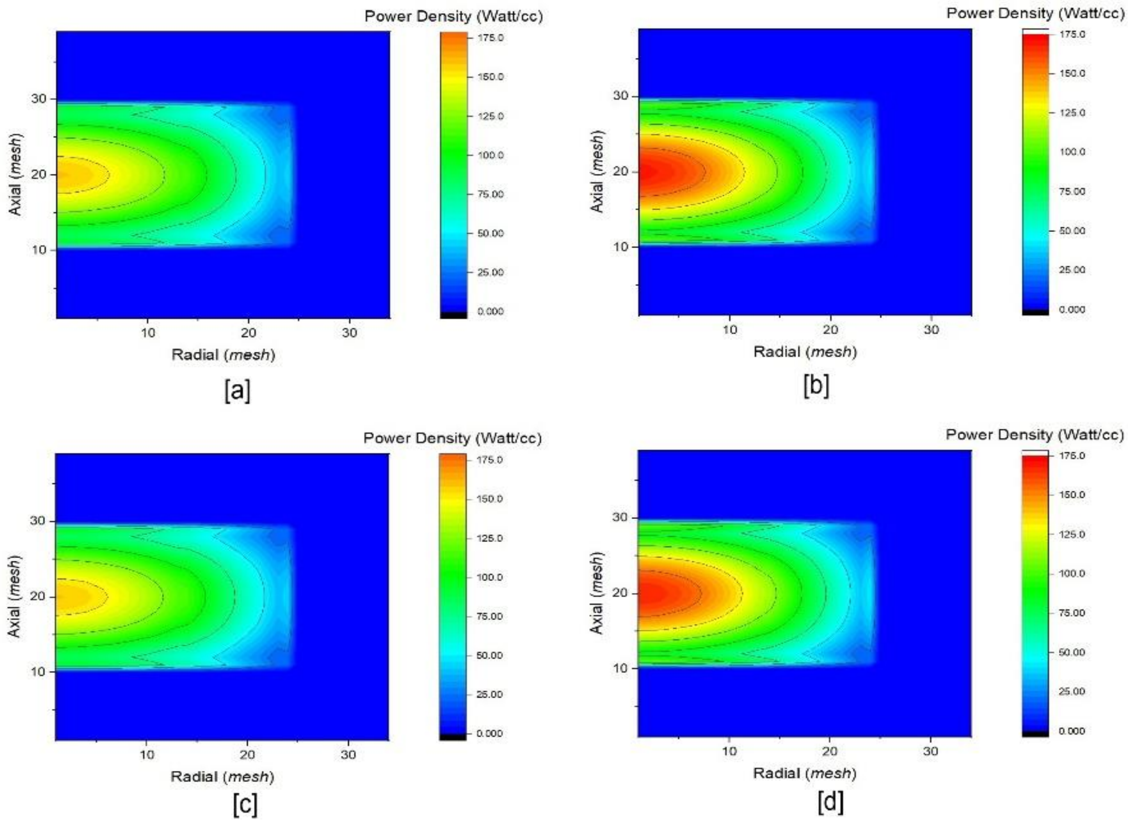


Figure 7. (a). Hexagonal pin cell power density in BOL phases; **(b).** Hexagonal pin cell power density in EOL phases; **(c).** Square pin cell power density in BOL phases; **(d).** Square pin cell power density in EOL phases

4. Conclusions

The homogenous core variations with hexagonal and square pin cell configurations reached optimum criticality at an enrichment of 12%. In the heterogeneous setup with enrichment variations F1, F2, and F3 at 11.5%, 12%, and 12.5%, the hexagonal pin cell achieved optimal criticality at a fuel fraction of 51%, while the square pin cell required 59% fuel fraction. Based on the power distribution results for both optimal designs, at Beginning of Life (BOL), both designs peaked at 159 watt/cc. In contrast, at End of Life (EOL), the hexagonal pin achieved a higher peak power, specifically 170 watt/cc, compared to 169 watt/cc for the square pin. These findings indicate that the hexagonal pin configuration may be a better choice as it achieves a slightly higher maximum power at EOL and BOL while requiring less fuel material to maintain reactor burn-up over the same period.

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